

# On the Distribution Function of the Complexity of Finite Sequences

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**Abstract** - Investigations of complexity of sequences lead to important applications such as effective data compression, testing of randomness, discriminating between information sources and many others. In this paper we establish formulas describing the distribution functions of random variables representing the complexity of finite sequences introduced by Lempel and Ziv in 1976. We show that the distribution functions depend in an affine way on the probabilities of the so called "exact" sequences.

**Keywords :** Complexity of sequence, distribution function, combinatorial problems, Lempel-Ziv parsing algorithms, randomness

## I. INTRODUCTION

The notion of complexity of a given sequence was first introduced in papers by Kolmogorov [3] and Chaitin [1]. Kolmogorov proposed to use the length of the shortest binary program which, when fed into a given algorithm, will cause it to produce a specified sequence, as a measure for the complexity of that sequence with respect to the given algorithm. If the length of the program is large we can say that the complexity of the sequence is large.

In 1976 Lempel and Ziv [4] proposed and explored another approach to the problem of the complexity of a specific sequence. They linked the complexity of a specific sequence to the gradual buildup of new patterns along the given sequence. The com-

plexity measure suggested by them is related to the number of distinct phrases and the rate of their occurrence along the sequence. It reflects the behaviour of a simple parsing algorithm whose task is to recognize newly encountered phrases during its scanning of a given sequence. In a series of papers, modifications of the Lempel-Ziv parsing algorithm were proposed in response to the needs of various applications. In general, in these algorithms a new phrase is established as the shortest substring which has not occurred previously, where the search for previous occurrences may be restricted or generalized in the modified algorithms in various ways, e.g.: by considering only a fixed number of preceding symbols [8], by considering only complete previously established phrases (Lempel-Ziv Incremental Parsing Algorithm [9]), by allowing a number (not more than a fixed threshold) of previous occurrences of the phrase (Generalized Lempel-Ziv Algorithm [6]) etc..

It turned out that investigations of sequence complexity play an important role in universal data compression schemes and their numerous applications such as efficient transmission of data [8],[9], tests of randomness [16], discriminating between information sources [2], [10], estimating the statistical model of individual sequences [10] and many others.

In this paper we introduce the concept of exact sequences i. e. sequences in which the last phrase of the sequence does not occur in the past (precise formulation: Def. 3). We derive formulas describing the distribution function of random variables representing the complexity of finite sequences as defined by Lempel and Ziv in 1976. These formulas turn out to be of affine form with respect to the probabilities of exact sequences.

## II. LEMPEL-ZIV COMPLEXITY

In this section we introduce the notation and recall basic definitions [4].

Let  $\mathcal{A}$  be a finite alphabet and let  $\alpha = |\mathcal{A}|$  denote the size of the alphabet. Let  $\mathcal{A}^n$  be the set of all sequences of length  $n$  over  $\mathcal{A}$  and let  $S = s_1 s_2 \dots s_n$  be an arbitrary element of  $\mathcal{A}^n$ . By  $S(i, j)$  we denote the substrings  $s_i s_{i+1} \dots s_j$  of  $S$  when  $i \leq j$  and  $S(i, j) = \Lambda$  when  $j < i$ . The partition

$$H(S) = S(1, h_1) S(h_1 + 1, h_2) \dots S(h_{m-1} + 1, n) \quad (1)$$

of  $S$  such that for every  $i$ ,  $S(h_{i-1} + 1, h_i - 1)$  is a substring of  $S(1, h_i - 2)$  is called the history of  $S$  and the  $m$  strings  $H_i(S) = S(h_{i-1} + 1, h_i)$ ,  $i = 1, 2, \dots, m$  where  $h_0 = 0$  and  $h_m = n$ , are called the components of the history. (Note that  $h_1 = 1$ ). Let  $c_H(S)$  denote the number of components in a history  $H(S)$  of  $S$ .

*Definition 1:* The complexity  $c(S)$  of the sequence  $S$  is the number

$$c(S) = \min\{c_H(S)\} \quad (2)$$

where the minimum is over all histories of  $S$ .

*Definition 2:* The component  $H_i(S) = S(h_{i-1} + 1, h_i)$  is called *exhaustive* if this string does not appear in the string  $S(1, h_i - 1)$ . A history of  $S$  is called *exhaustive* if each of its components, except possibly the last one, is exhaustive.

It is easy to see that every sequence has a unique exhaustive history, denoted by  $H_E(S)$ . For instance, the exhaustive history of the sequence  $S=0011011101110110$  is given by the following parsing of  $S$ : 0, 01, 10, 111, 0110110 where successive components are separated by commas.

*Remark 1:* It was proved in [4] that  $c(S) = c_E(S)$ , where  $c_E(S)$  is the number of components in  $H_E(S)$ . Thus, below we shall use  $c_E$  as the definition of complexity.

*Definition 3:* The sequence  $S = s_1 s_2 \dots s_n$  is called *exact* if the last string  $S(h_{m-1} + 1, n)$  in its exhaustive history  $H_E(S) = S(1, h_1)S(h_1 + 1, h_2) \dots S(h_{m-1} + 1, n)$  does not occur as a substring  $S(i, j)$  (where  $1 \leq i \leq j \leq n - 1$ ) in the sequence  $S(1, n - 1) = s_1 \dots s_{n-1}$ .

From now on we shall assume that for a fixed  $n$  any element of  $\mathcal{A}^n$  is equiprobable, i.e. we assign the same probability  $\alpha^{-n}$  to each element of  $\mathcal{A}^n$  and

$$P_n : 2^{\mathcal{A}^n} \rightarrow [0, 1] \quad (3)$$

denotes the probability in this sense. By  $P_n(k)$  we denote the probability of the event consisting of all sequences of length  $n$  and complexity  $k$  while  $P_n(k_e)$  is the probability of the event consisting of all exact sequences of length  $n$  and complexity  $k$ .

Under the above assumptions for every  $n \in \mathbb{N}$  we define the random variable  $C_n : \mathcal{A}^n \rightarrow \mathbb{N}$  representing the complexity:

$$C_n(S) := c_E(S) \quad (4)$$

for every sequence  $S \in \mathcal{A}^n$ .

### III. THE DISTRIBUTION FUNCTION OF $C_n$

In this section we describe the distribution function of  $C_n$ ,  $n \in \mathbb{N}$ . We prove the following

**Theorem:** Under the above notation,

$$P_{n+1}(C_{n+1} \leq k) = 1 - \sum_{r=1}^n P_r(k_e) \quad (5)$$

for every  $n, k \in \mathbb{N}$ .

*Proof:* We first express  $P_{n+1}(k+1)$  in terms of  $P_n$ .

By definition of  $P_n$  we find that:

- the number of sequences with complexity  $k+1$  and length  $n$  is  $\alpha^n P_n(k+1)$ ,
- the number of exact sequences with complexity  $k+1$  and length  $n$  is  $\alpha^n P_n((k+1)_e)$ ,
- the number of exact sequences with complexity  $k$  and length  $n$  is  $\alpha^n P_n(k_e)$ .

Taking into account the definitions of complexity and exact sequences we conclude that every sequence with complexity  $k+1$  and length  $n+1$  can be obtained from a sequence of length  $n$  in one of the following two ways only:

- by adding a symbol to a sequence with complexity  $k+1$  which is not exact,
- by adding a symbol to an exact sequence with complexity  $k$ .

We also see that all sequences obtained from exact sequences of length  $n$  and complexity  $k+1$  by adding a symbol from  $\mathcal{A}$  will increase their complexity to  $k+2$  and the number of such sequences is  $\alpha \cdot \alpha^n P_n((k+1)_e)$ . From the definition of  $P_{n+1}(k+1)$  and the above observations we conclude that

$$P_{n+1}(k+1) = \frac{\alpha \cdot \alpha^n P_n(k+1) - \alpha \cdot \alpha^n P_n((k+1)_e) + \alpha \cdot \alpha^n P_n(k_e)}{\alpha^{n+1}} \quad (6)$$

and thus

$$P_{n+1}(k+1) = P_n(k+1) + P_n(k_e) - P_n((k+1)_e) \quad (7)$$

for every  $n, k \in \mathbb{N}$ .

Replacing  $n + 1$  by  $n$  we have

$$P_n(k + 1) = P_{n-1}(k + 1) + P_{n-1}(k_e) - P_{n-1}((k + 1)_e) . \quad (8)$$

Substituting (8) into (7) we obtain

$$P_{n+1}(k + 1) = P_{n-1}(k + 1) + P_{n-1}(k_e) - P_{n-1}((k + 1)_e) + P_n(k_e) - P_n((k + 1)_e) . \quad (9)$$

We replace  $n$  by  $n - 1$  in (8) and insert the result in (9). Continuing this process we arrive at

$$P_{n+1}(k + 1) = P_1(k + 1) + \sum_{r=1}^n [P_r(k_e) - P_r((k + 1)_e)] . \quad (10)$$

Since  $P_1(k + 1) = 0$  for  $k \geq 1$  we have

$$P_{n+1}(k + 1) = \sum_{r=1}^n P_r(k_e) - \sum_{r=1}^n P_r((k + 1)_e) \quad (11)$$

for every  $k, n \in \mathbb{N}$ .

Now, replacing in (11)  $k$  by  $k + 1, k + 2, k + 3, \dots, k + (n - k) - 1$  we obtain

$$\begin{aligned} P_{n+1}(k + 2) &= \sum_{r=1}^n P_r((k + 1)_e) - \sum_{r=1}^n P_r((k + 2)_e) \\ P_{n+1}(k + 3) &= \sum_{r=1}^n P_r((k + 2)_e) - \sum_{r=1}^n P_r((k + 3)_e) \\ &\vdots \\ P_{n+1}(n) &= \sum_{r=1}^n P_r((n - 1)_e) - \sum_{r=1}^n P_r(n_e) . \end{aligned} \quad (12)$$

Adding (11) and the above equations and taking into account the fact that

$$\sum_{r=1}^n P_r(n_e) = 0 \text{ for } n \geq 2 \text{ we have}$$

$$\sum_{s=1}^{n-k} P_{n+1}(k + s) = \sum_{r=1}^n P_r(k_e) . \quad (13)$$

One can easily see that  $P_{n+1}(k + s) = 0$  for  $s > n - k$ , where  $n > k \geq 1$ .

Thus, we obtain the following expression for the distribution function of  $C_{n+1}$ :

$$P_{n+1}(C_{n+1} \leq k) = 1 - \sum_{r=1}^n P_r(k_e) , \quad (14)$$

which finishes the proof.

*Corollary 1:* For every  $n$  and  $k$ ,

$$P_{n+1}(C_{n+1} \leq k) = P_n(C_n \leq k) - P_n(k_e) . \quad (15)$$

*Proof:* From (14) we have

$$1 - \sum_{r=1}^{n-1} P_r(k_e) = P_n(C_n \leq k) . \quad (16)$$

Adding (14) and (16) we obtain (15).

*Remark 2:* It follows from the above corollary that  $P_{n+1}(C_{n+1} \leq k) \leq P_n(C_n \leq k)$ .

*Corollary 2:* From (14) and the fact that [4]

$$\lim_{n \rightarrow \infty} P_n(C_n \leq k) = 0 \quad (17)$$

we deduce that

$$\sum_{r=1}^{\infty} P_r(k_e) = 1 . \quad (18)$$

#### IV. FINAL REMARKS

The complexity of sequences was suggested as a statistical test of randomness of a random number generators and block ciphers [5], [7]. It was proved in [4] that  $\lim_{n \rightarrow \infty} P_n(C_n \leq \frac{n}{\log_{\alpha} n}) = 0$ . Therefore, the sets  $K_{n,k} := \{S \in \mathcal{A}^n : C_n(S) \leq k\}$  seem to be good candidates for critical sets (usually  $k$  is assumed [7] to be  $\frac{n}{\log_{\alpha} n}$ ). This means, in fact, that for an arbitrarily chosen probability  $p$  close to 0 there is  $n_0$  such that for  $n > n_0$ , for a given randomly chosen sequence  $S$  the inequality  $C_n(S) \leq \frac{n}{\log_{\alpha} n}$  holds with probability less than  $p$ . Thus, it is essential to estimate  $P_n(K_{n,k}) = \sum_{s=1}^k P_n(s)$ , i.e. the levels of significance for  $K_{n,k}$ . In practice, for a fixed  $n$  these sums are computed numerically by finding all terms. Formula (15) makes it possible to find the probability  $P_{n+1}(K_{n+1,k})$  for sequences of length  $n+1$  from the probabilities  $P_n(K_{n,k})$  and  $P_n(k_e)$  for sequences of length  $n$  (the latter two can be calculated simultaneously). This reduces the computation time.

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